Application of the HEC6T Model to Assess Post-fire Channel Remediation Alternatives

H. Evan Canfield[1], Cathy J. Wilson[2], Leonard J. Lane[1,2], William A. Thomas[3], Kelly J. Crowell[2], T. Andrew Earles[4]

[1] USDA-ARS Southwest Watershed Research Center, 2000 E. Allen Rd., Tucson, AZ 85719 ecanfield@tucson.ars.ag.gov (520) 670-6370 x145 FAX (520) 670-5550
[2] EES-2 Atmospheric Climate and Environmental Dynamics, Los Alamos National Laboratory, Los Alamos, NM 87545
[3] Mobile Boundary Hydraulics, PO Box 264 Clinton, MS 39056
[4] Wright Water Engineering, 2490 W. 26th Avenue, Suite 100A Denver, CO 80211

Abstract

Increased flood peak discharge and sediment load have been observed following the Cerro Grande Fire in Los Alamos, New Mexico. Because of concerns about the potential migration of radionuclides, a sediment transport model, HEC6T, was used to describe the observed scour, deposition and sediment transport in the wake of the fire. The model was then used to evaluate a grade-stabilization alternative in the portions of the channel, which the model predicted would be the most adversely impacted by post-fire scour. A fifty-year simulation was used to test the effectiveness of grade control - relative to taking no action. The simulation showed that the most upstream grade stabilization structure trapped the most sediment. Scour could occur below the structures. By causing sediment to deposit on the upstream side of the structure, the water flowing over the structure is able to scour because transport capacity is above the concentration in the flow. Overall, the simulations showed that grade stabilization can be an effective method for reducing scour. However, the design and emplacement of the structures requires analyses and interpretation accounting for hydrology, hydraulics, sediment transport and sediment yield.

Introduction

In May 2000, the Cerro Grande Fire burned a total of 17,400 hectares, including about 85% of the steep forested lands in the headwaters of streams that flow through Los Alamos County, the Los Alamos National Laboratory (LANL), and Pueblos located in the Jemez Mountains and on the Pajarito Plateau in Northern New Mexico. Much of this was high severity burn, which burned both trees and the underlying duff layer. The fire preceded the summer rainy season, which is characterized by intense convective rain events. Flood peaks following the fire increased by one or more orders of magnitude relative to pre-fire flood peaks (Canfield et al, (in press). Roads, buildings, sewer lines and other infra-structure located in canyon bottoms were damaged by post-fire flooding and coincident sedimentation and scour. Of particular concern is the fact that sediment in some of the canyons downstream of LANL

facilities contains low levels of residual contaminants from weapons related activities during and following the Manhattan Project (Lane, et al., 1985;Graf, 1994; Reneau et al., 1998). Concern over the impact of post-fire hydrologic processes on human safety, facilities and infrastructure prompted the development and application of models to assess the likely magnitude of post-fire flooding (Earles et al, 2004; McLin et. al 2001) and its impact on sediment and contaminant transport (Wilson et al. 2003;Wilson et. al 2001; Canfield et al (in press))

The HEC6T model was calibrated against cumulative volume change determined by ALSM (Airborne Laser Scanning Mapping) digital electronic data collected in July, 2000 and November, 2001. This period included a 40 m^3/s event that has been estimated to be a 5-year post-fire event (Earles et al, pers. comm., 2003). This event was approximately two orders of magnitude greater than the peak discharge of 0.3 m^3/s measured in the seven-year period of record prior to the fire. The determination of the cumulative volume change is the subject of a separate paper. The results of the sensitivity analysis and model calibration are also described elsewhere (Canfield et al. (in press)).

The observed pattern of scour and deposition in Pueblo Canyon strongly mirrors the channel gradient, and the calibrated HEC6T model describes this pattern. The presumed source of the plutonium in Pueblo Canyon is Acid Canyon, a tributary in upper Pueblo Canyon (Reneau et al, 1998). From Acid Canyon to about station 7770 m (stationing in m above the confluence of Pueblo Canyon with Los Alamos Canyon), the channel is steep (>2%), but with very little stored alluvium. From station 7770 m to station 3660 m, the channel profile is linear with a gradient of about 1%, and deposition has been observed to occur. The lower reach, from the 3660 m to the outlet of Pueblo Canyon (i.e. station 0), has a convex profile with a gradient that increases to about 2%. The model predicted that the channel would scour in the upper and lower reaches, and agrade in the middle reach. However, the lowest portion of the channel from about 2600 m to the confluence with Pueblo Canyon was predicted to experience the greatest volume of scour, and was, therefore, predicted to be at the greatest risk to mobilize contaminants (Wilson et al. 2003).

An investigation aimed at assessing the usefulness of the HEC-6T sediment transport model (Thomas, 2003) in evaluating the performance of grade control structures in Pueblo Canyon was undertaken as part of the proposed remediation activities. This study uses the calibrated HEC6T model to consider the predicted effect of grade control on Pueblo Canyon near Los Alamos, New Mexico below burned watersheds.

Grade Control

Grade control is one of the most common methods used to reduce scour in gullies and channels. The concept of these structures is simple. Raising and stabilizing the bed of a channel at intervals reduces the average slope of the channel bed, thus contributing to a net decrease in the transport capacity of the flow, and total shear exerted on the bed. This cannot only prevent scour. It can cause deposition of the

coarser particles in the flow. While grade control clearly traps sediment upstream of the grade control structure, some analyses have concluded that net change in stored sediment may be small (Simon and Darby, 2002). These authors' analysis indicates that the grade control must be installed above a nick point so as to prevent the migration of the nick point upstream. Furthermore, they note that while the grade control structure traps sediment, more scour may occur downstream of a structure, because the flow may be above transport capacity for some particle size classes, thus contributing to downstream scour that may be greater than would occur in the absence of the structure.

Objective

The objective of this study is to determine the relative impact of grade control on preventing the migration of sediment containing residual concentrations of radionuclides in the lowest 2600 m of Pueblo Canyon. The concept was to cover these sediments with cleaner sediment derived from further upslope (Figure 1).

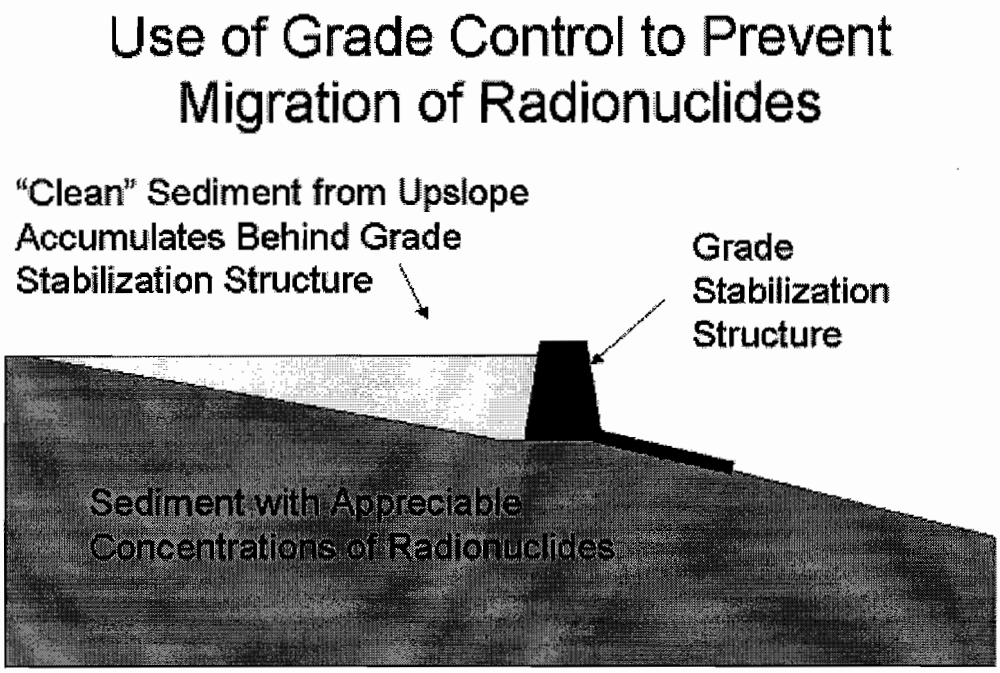

Figure 1 – Example of the proposed use of grade control to limit scour of sediment with radionuclides.

Methods

The study describes the impact of grade control on stabilizing sediment upstream of structures relative to the no action alternative using the HEC6T model to evaluate this impact when subjected to a 50 year stochastic flow sequence.

Grade control was designed to focus on stabilization of the channel bed in the lower reach of Pueblo Canyon where the model predicted significant bed degradation and channel instability under baseline conditions of no grade control. The design featured grade control structures located every 152 m from below cross-section 2590 m to the confluence of Pueblo and Los Alamos canyons. This scenario aimed to decrease the slope of the lower reach of Pueblo Canyon from about 2 % to about 1%.

The HEC6T Model

HEC6T (Thomas, 2003) is a one-dimensional sediment transport model that couples the solution of the gradually-varied form of the Saint Venant Equations with the five basic sedimentation processes: erosion, entrainment, armoring transportation, deposition and the compaction of sediment. The HEC6T Model is an update of the widely-used United States Army Corps of Engineers HEC6 Model (USACE, 1995). HEC6 has been used to model scour and deposition in channels (Sinnakaudan et al. 2003; Zeng and Beck 2003). HEC6T allows scour and deposition to be described at a cross-section, with a reach being characterized by the space between the two cross-sections. For each reach, the sediment available for scour can be envisioned as a control volume with a given width, depth and length.

Classical, non-cohesive sediment transport functions are used for sand and larger particles (> 0.0625 mm), and cohesive sediment transport functions are used for silts and clays (< 0.0625 mm). The empirical coefficients, that are required for the cohesive functions, can be prescribed in the input data. For this simulation the Yang (1973) total load sediment transport capacity equation was used to calculate sediment transport and deposition.

Structural Implementation of Grade Control in HEC6T

The grade control structures in the lower reach of Pueblo Canyon were implemented in the model by modifying existing HEC6T cross-sections so that the top elevation of the cross-section was 1.5 m above the level of the bed. The erodible depth parameter was set to zero at these cross sections. In addition, erodible depth was set to zero in the two cross-sections downstream of the grade control cross-section. This aimed to simulate engineered armoring below the grade control structures, and allowed predicted flow velocities on the downstream side of the structure to stabilize as they would under actual conditions.

The design also included representation of buried grade control in the upper reach of Pueblo Canyon. These structures, installed perpendicular to flow and level with the elevation of the existing bed, aim to limit scour without trapping sediment. The structures were implemented in the model by assigning a value of zero to the erodible depth parameter at the HEC6T cross-section representing the structure. The specifications for the revised grade control structures are given in Table 1.

Table 1 - Specifications for positions and heights of modeled grade control structures

Upstream cross-section ID number	Downstream cross-section ID number	Number of structures between cross-sections	Approximate distance between cross-sections	Bed height above Thalweg
(distance upstream along thalweg in meters)	(distance upstream along thalweg in meters)		(m)	(m)
2599	149	17	152	1.52
4029	2802	10	152	0
5643	4883	6	152	0
5968	5802	2	152	0
7143	6829	3	152	0
Total		38		

Post-Fire Discharge

To test whether the implementation of grade control is predicted to be effective, a series of post fire flow events was prepared using stochastic methods. These events focused entirely on events that occur in the summer monsoon at soon after post-fire conditions. Runoff rates are known to decline over time as the watershed recovers (e.g. Robichaud et al. 2000). This recovery was not considered in these simulations in order to assume a conservative (i.e. worst case) scenario.

Post-fire peak discharges were dramatically higher than pre-fire peak discharges. After the fire, the previous peak discharge of 0.31 m^3/s for the previous seven years was exceeded numerous times. A peak discharge of 40 m^3/s was measured on July 2, 2001 and six events greater than 3 m^3/s were observed between June 2000 and July 2001. Based on post-fire runoff modeling, this event has approximately a 5-year return period event (Earles, pers. comm. 2003). Using this series of events from June 2000 to July, 2001, as well as the peak discharge events from 2002 (16.4 m^3/s) and 2003 (28.3 m^3/s), a fifty year long post-fire sequence of runoff hydrographs was prepared to evaluate the effectiveness of grade control scenarios. The stochastic method assumed that on average, six events occurred each year with a maximum of 10 events in a year, and a minimum of 6 events in a year. Using this method, the 40 m^3/s event occurred in 12 of 50 years (i.e. 24% of the time), which is once every 4 years, slightly more frequently than every five-years. In each year events occur in random order.

Results

The model predicted the greatest influence of grade control on bed scour and deposition in the lower reach of Pueblo Canyon. The model predicted 1 to 2 m. of scour along the bottom 2600m of Pueblo Canyon for the no action scenario. In contrast, the grade control structures caused significant bed agradation in the channel. Figure 2 shows that after 50 years of simulated floods, most of the structures have filled in a crest to toe manner.

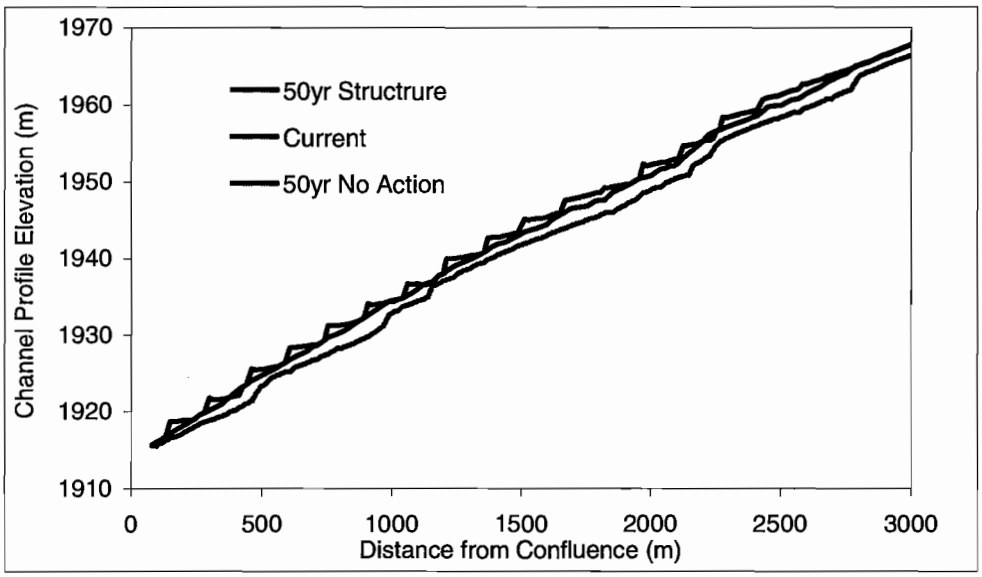

Figure 2 - The model predicts that after 50 years, the no action scenario (solid red line) will result in significantly more scour through the lower reach of Pueblo Canyon than the grade control scenario (blue solid line). The black solid line shows the "pre-fire" profile of the bed.

In Figure 2, the grade control profile is just slightly higher than the base profile, while the no-action profile is clearly below the base profile. The figure shows that the depth of scour without the structures will be greater than the depth deposited with the structures in place. While the model predicts scour below some structures (e.g. downstream of second structure at ~2,200m), the final grade control profile is higher than the predicted no-action alternative profile for the entire profile.

While the scour depth is greater than the deposition depth in figure 2, the volume increase from grade control is much greater than the predicted volume decrease from scour in the no-action alternative as indicated in Figure 3.

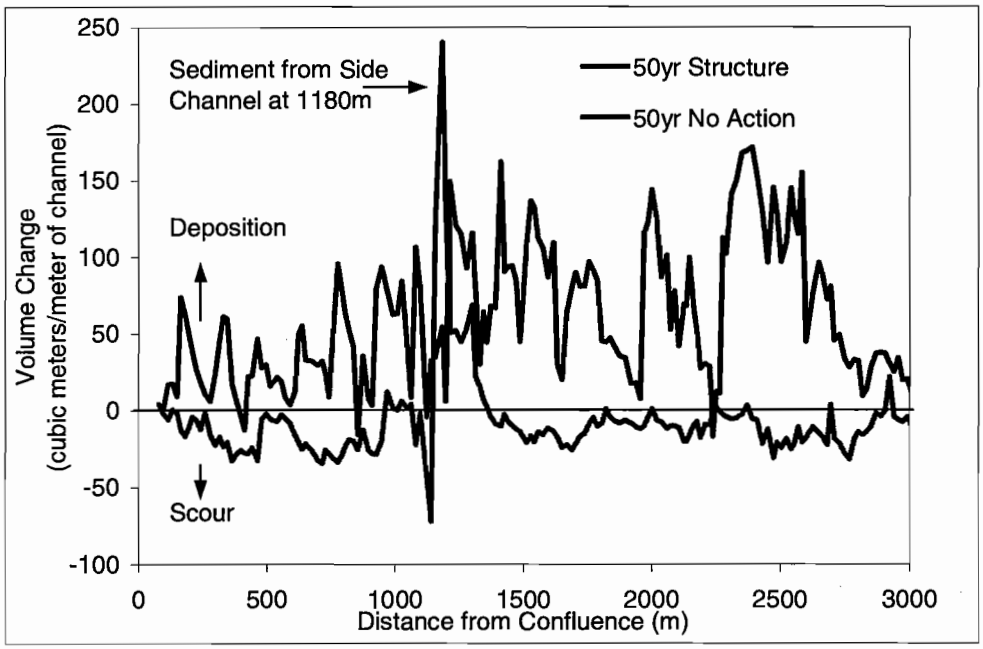

Figure 3 - The blue line shows the simulated volume of scour or deposition in the channel at the end of the 50 yr simulation with structures in place (cubic meters/meter of channel). The red line shows the simulated volume change in this reach without the structures.

The apparent greater scour along the profile than deposition occurs, because scour tends to incise the narrowest portion of the channel, while deposition fills to the widest limits of the grade control structure. Therefore, the impact of the grade control is to deposit more material behind the structures than would be scoured if the structures were not in place.

Impact of Grade Control on Sediment Yield and Export of Fines

The model also predicted that the grade control would trap a significant amount of course and fine sediment. Table 2 summarizes the effectiveness of grade control as a sediment trap as a function of time. It is important to distinguish the effectiveness of trapping for both fine and coarse sediment. Trapping of fines is of particular concern, because plutonium adsorbs strongly to particles, so more plutonium is transported on fine particles that have a higher specific surface area.

At the end of five years the model predicted that the grade control structures would trap 74% of the coarse material and 26% of the fines moving through Pueblo Canyon. At the end of 50 years, the structures would have trapped 30% of the coarse material and 19% of the fines moving through the system. Although the effectiveness of grade control as a sediment trap is predicted to decrease with time, the structures act to

stabilize bank material upstream of the structure, making contaminated bank material unavailable for transport.

Table 2 - Summary of impact of grade control on sediment transport

Simulation Year	Material Type	No Structures, Tons Passed	With Structures, Tons Passed	Tons Trapped by Structures	% Trapped
5	Sand and Larger	171,969	44,734	127,235	74.0%
10	Sand and Larger	335,553	137,391	198,162	59.1%
15	Sand and Larger	516,816	266,459	250,358	48.4%
20	Sand and Larger	657,029	366,344	290,685	44.2%
25	Sand and Larger	829,965	498,006	331,959	40.0%
30	Sand and Larger	935,895	578,032	357,863	38.2%
35	Sand and Larger	109,4685	709,394	385,290	35.2%
40	Sand and Larger	123,8985	831,448	407,537	32.9%
45	Sand and Larger	138,2863	954,006	428,857	31.0%
50	Sand and Larger	1,475,364	1,034,074	441,290	29.9%
5	Silt and Clay	107,396	79,523	27,874	26.0%
10	Silt and Clay	205,079	157,738	47,340	23.1%
15	Silt and Clay	308,410	241,647	66,763	21.6%
20	Silt and Clay	387,885	306,722	81,163	20.9%
25	Silt and Clay	485,081	387,056	98,025	20.2%
30	Silt and Clay	544,563	436,486	108,076	19.8%
35	Silt and Clay	632,486	509,796	122,689	19.4%
40	Silt and Clay	714,289	578,226	136,063	19.0%
45	Silt and Clay	797,686	647,945	149,741	18.8%
50	Silt and Clay	851,237	692,658	158,579	18.6%

Discussion

Other studies have noted that a series of grade control structures can have the effect of excessive deposition on the upstream end, and excessive scour downstream of the last structure. Simon and Darby (2002) studied the effect of grade control downstream of structures in loess (silt and silt loam) soils in Mississippi. A series of grade control structures were installed in 1980, which resulted in a net increase in the volume of deposition behind the structures. However, the study concluded that net scour would occur in the reach as a whole, because more scour would occur downstream of the last structure as the stream returned to transport capacity. The study showed a moderate decrease in trapped sediment from the upper to the lower structures.

While this decrease from upper to lower structures is much more pronounced for the simulations at Pueblo Canyon, the sediment at Pueblo Canyon is much coarser than the sediment from loess streams in Mississippi. In Pueblo Canyon, sediment is transported in high-discharge, ephemeral flows, with an appreciable coarse bed load, which is likely to be trapped uspstream of a structure. This is in contrast to the silt loam soils in Simon and Darby's (2002) study, which are more likely to be transported as suspended load, and may be more readily transported over a structure.

An alternative approach would be to place the structures at a shorter spacing, so as to reduce the gradient to virtually zero. Lenzi and Comiti (2003) studied the effect of grade control on stabilizing a mountain stream in the Alps. Unlike the scenario used in Pueblo Canyon, these grade stabilization structures had a reverse grade (i.e. downstream crest is above the toe of the upstream structure). The net effect of these structures was to trap sediment, and decrease the particle size of sediment passing to the next downstream structure. There was no protection below the structures, and a plunge pool formed below most of the structures. Downstream of the plunge pools, if the distance between structures was large enough, sediment was deposited downstream of the plunge pools, thus raising the bed. If the distance between structures was too short, the plunge pools extended to the next downstream structures. Therefore, there may be a risk in placing structures too close together, and certainly the cost would be greater.

Conclusions

Although model predictions show that appropriately designed grade control provides sediment and thus, contaminant trapping benefits, this modeling activity was primarily aimed at examining the efficacy of using HEC6T to evaluate remediation options in Pueblo Canyon. The study demonstrated that HEC6T can be used to evaluate and optimize engineering options to control sediment and contaminant transport in canyons at Los Alamos.

The model runs showed that grade control could be effective at stabilizing plutonium-bearing sediments subjected to a 50 year simulation of high discharge, sediment-rich events. It did not address the effectiveness of other remediation solutions. Modeling would provide a means to optimize a design for plutonium transport control that can be both effective and cost efficient.

Acknowledgements

The authors appreciate the support and assistance provided by the Cerro Grande Fire Modeling team, especially Everett Springer and Steve Rae (LANL), who directed the effort. We gratefully acknowledge the financial support provided by Steve Mee of LANL. Institutional support for this work was provided by the USDA-ARS Southwest Watershed Research Center and M. Susan Moran, it's Research Leader.
LANL Document Number: LA-UR-05-0707

References

Canfield, H.E., Wilson, C.J., Lane, L.J., Crowell K.J and Thomas, W.A. (in Press) *"Modeling Scour and Deposition in Ephemeral Channels after Wildfire"*, (accepted for publication in CATENA)

Earles, T.A., Wright, K.R., Brown, C. and Langan, T.E. (2004) *"Los Alamos Forest Fire Impact Modeling."* Journal of the American Water Resources Association. 40, 371-384

Earles, pers. comm. 2003

Graf, W.L., (1994). *Plutonium and the Rio Grande, Environmental Contamination in the Nuclear Age.* Oxford University Press, Inc.: New York.

Lenzi, M.A. and Comiti, F. (2003) "Local Scouring and Morphological Adjustments in Steep Channels with Check-dam Sequences." *Geomorphology.* 55 (2003) 97–109

Lane, L. J., Purtymun, W. D., Becker, N. M., (1985). *New Estimating Procedures for Surface Runoff, Sediment Yield and Contaminant Transport in Los Alamos County, NM.* Los Alamos National Laboratory Report LA-10335-MS

McLin, S. G., Springer, E. P., and Lane, L. J. (2001). "Predicting Floodplain Boundary Changes Following the Cerro Grande Wildfire." *Hydrological Processes* 15(15) 2967-2980.

Reneau, S., Ryti, R., Tardif, M., and Linn, J. (1998). *Evaluation of Sediment Contamination in Pueblo Canyon. Reaches P-1, P-2, P-3, and P-4.* LA-UR-98-3324, Los Alamos National Lab., Sept., 1998, 431 pp.

Reneau, S. L., Drakos, P. G., Katzman, D., Malmon, D. V., McDonald, E. V., Ryti, R. T., (2003). *Plutonium in Pueblo Canyon, New Mexico: Geomorphic controls on contaminant distribution.* Los Alamos National Laboratory publication LA-UR-03-1654

Robichaud, P.R., Beyers, J. L., Neary, D.G., (2000). *Evaluating the Effectiveness of Postfire Rehabilitation Treatments.* United States Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR 63

Simon, A. and Darby, S.E (2002) "Effectiveness of grade-control structures in reducing erosion along incised river channels: the case of Hotophia Creek, Mississippi." *Geomorphology* 42. 229– 254

Sinnakaudan, S.K. Ghani, A.A., Ahmad, M.S.S , Zakaria, N.Z., (2003). "Flood risk Mapping for Pari River Incorporating Sediment Transport." *Environmental Modelling & Software.* 18, 119–130

Thomas, W. A., (2003). *Sedimentation in Stream Networks (HEC6T):* User's Manual Mobile Boundary Hydraulics

USACE. (1995). HEC6 V. 4.1, *Scour and Deposition in Rivers and Reservoirs: User's Manual.* Hydrologic Engineering Center, Davis, CA National Technical Information Service (NTIS) # PB94-501202

Wilson, C.J., Canfield, H.E., Crowell, K.J. and Lane, L.J. (2003) *Modeling the Impacts of the Cerro Grande Fire on Sediment and Plutonium Transport in Pueblo Canyon* Los Alamos National Laboratory publication LA-UR-03-6966

Wilson, C. J., Carey, J. W., Beeson, P. C., Gard, M. O., Lane, L. J., (2001). "A GIS-Based Hillslope Erosion and Sediment Delivery Model and its Application in the Cerro Grande Burn Area." *Hydrological Processes*. 15, 2995-3010.

Yang, C.T., (1973) "Incipient Motion and Sediment Transport." *Journal of the Hydraulics Division, ASCE.* 99, 323-338

Zeng, W., Beck, M.B., (2003). "STAND, a Dynamic Model for Sediment Transport and Water Quality." *Journal of Hydrology.* 27, 125-133.